EVALUATION OF SPLASH AND SPRAY SUPPRESSION DEVICES

ON LARGE TRUCKS DURING WET WEATHER

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FOREWORD

This study was funded by the AAA Foundation for Traffic Safety. Founded in 1947, the AAA Foundation is a not-for-profit, publicly supported charitable research and educational organization dedicated to saving lives and reducing injuries by preventing traffic crashes.

This peer-reviewed report documents two experiments intended to examine the effectiveness of several commercially available spray devices that can be attached to large trucks to reduce splash and spray during wet weather conditions.

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If trade or manufacturers' names or products are mentioned, it is only because they are considered essential to the object of this report and their mention should not be construed as an endorsement. The AAA Foundation for Traffic Safety does not endorse products or manufacturers.

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EXECUTIVE SUMMARY

Spray produced by large trucks in wet weather creates poor visibility for all drivers. This condition is of great concern, as reduced vision caused by spray can jeopardize drivers' safety. To address this problem, several truck and equipment manufacturers have developed aerodynamic truck designs and aftermarket devices to suppress spray. In past years these devices have been evaluated to determine their effectiveness in limiting spray. However, in recent years new devices have been developed that have not had their spray suppression capability evaluated.

To address this problem, Texas Transportation Institute (TTI) first identified devices, technologies, and practices that purported to produce less spray from large trucks and were developed since 1990. TTI then identified European Union initiatives for the suppression of spray from large trucks. Finally, TTI employed an alternative spray testing methodology to examine the suppression of spray for North American large trucks.

Evaluation of spray-suppressing devices was conducted at TTI's test facility near Bryan, Texas. Two measurement methods were employed simultaneously: the laser-based method detailed by SAE Recommended Practice J2245 and a modified video-based method similar to that also detailed in SAE Recommended Practice J2245. Although both methods have been used successfully in the past, using both methods simultaneously for this evaluation provided two sets of results for comparison and provided stronger conclusions about the performance of the devices tested.

Five devices that purported to produce less spray for large trucks during wet weather conditions were pilot tested. Each device was mounted on a 1985 Freightliner tractor-trailer combination. An older, non-aerodynamic tractor-trailer was employed because of that configuration's more effective ability to show differences among the devices. Pilot testing consisted of performing 8 runs for each device in a right crosswind at 55 mph (88.5 kph). A single wind condition was employed because collecting data in all wind conditions was impossible due to time and financial considerations. Pilot testing these devices on each particular tractor-trailer combination indicated which anti-splash and spray device proved most effective.

To test the effectiveness of four spray combinations on four tractor-trailer configurations traveling at 55 and at 65 mph (88.5 and 104.59 kph), 32 runs were made in each of 4 configurations. Configuration 1 was a 1997 Freightliner tractor-trailer with no spray devices, configuration 2 was the same 1997 Freightliner tractor-trailer outfitted with the most effective spray device from pilot testing, configuration 3 was a 1985 Freightliner tractor-trailer outfitted with no spray devices, and configuration 4 was the same 1985 Freightliner tractor-trailer outfitted with the most effective spray device from pilot testing.

This arrangement indicated which, if any, of the four configurations produced the least amount of spray on those particular tractor-trailer combinations, whether the spray treatment was effective at a variety of vehicle speeds, and the role of vehicle aerodynamics in the production of spray. The plan for all testing followed the Society of Automotive Engineers recommended practice for splash and spray evaluation (SAE J2245 paragraphs 6.2, 6.3.2, 6.4, 6.4.2 (1994)), without exception.

The results of the present investigation indicated that at the lower vehicle speed, regardless of the wind condition, the addition of spray reduction devices to the 1997 newer and more aerodynamic tractor-trailer configuration did not result in a significant reduction of spray. Consistent with these results, testing at the higher vehicle speed indicated no significant differences between the improved aerodynamic tractor-trailer without spray reduction devices and the improved aerodynamic tractor-trailer with such devices, for any wind condition. Although not significant, results indicated the addition of spray reduction devices to the less aerodynamic 1985 tractor-trailer may slightly reduce spray at lower vehicle speeds in non-stringent wind conditions, but provide no benefit at higher vehicle speeds.

The results indicated that an improvement in the aerodynamics of a tractor-trailer configuration can significantly reduce the amount of spray generated by large trucks in wet weather. Therefore, although the addition of the evaluated devices does not significantly reduce spray, improved vehicle aerodynamics can reduce spray and are of more benefit. The results of this investigation also support the contention that laser- and video-based methodologies produce highly correlated results.

INTRODUCTION

The impetus for research and development for spray suppression devices in the United States dates back to the 1970s with great interest arising in the early 1980's with the National Highway Traffic Safety Administration's (NHTSA) concerns about the safety implications of drivers being blinded by heavy truck spray for long moments during wet weather. Early studies in the United States were performed by the Western Highway Institute, Systems Technology Inc., the Transportation Research Center of Ohio, and other groups. In 1982, there were words in the Surface Transportation Assistance Act to the effect that "visibility on wet roadways on the Interstate System should be improved by reducing, by a practicable and reliable means, splash and spray from truck tractors, semi trailers and trailers".

The approaches to measuring spray from trucks have evolved from subjective estimates by observers on the highway or viewing filmed records to the present Society of Automotive Engineers (SAE) vehicle recommended practice J2245 (1994). There have also been wind tunnel approaches for evaluating individual wheel or axle treatments, an approach once under serious consideration by NHTSA. The J2245 instrumented test pad, using the entire vehicle, was originated by Systems Technology Incorporated (Weir, 1978), employed by STI in a series of tests (Johnson, Stein, & Hogue, 1985; Johnson, Stein, & Hogue, 1987; Weir, Strange, & Heffley, 1978) and used for a series of studies by TTI during the period of 1984-1990. In a parallel development, PACCAR, the parent company for Peterbilt and Kenworth trucks, refined the alternative image digitization approach, also in J2245. TTI studied this method in 1990 and found that it gave equivalent (highly correlated) figures of merit to those obtained using the laser transmissometer method (Koppa, Pezoldt, Zimmer, Deliman, & Flowers, 1990).

The 1980's research centered around add-on devices to suppress the spray (cloud of mist) that arises when the water on the tire treads strikes hard surfaces on the truck and is then blown or sucked to the side of the vehicle. These devices included different designs of flaps that were all (1) stiffer than conventional "mud flaps" and (2) had some kind of bristle or other treatment on the inner surface to absorb the water thrown on them from the tire and let it drip onto the pavement. Other devices installed with or without absorbent flaps were "skirts" that hung down from the structure above the wheels to form a kind of fender enclosure to contain spray but still allow some airflow to ventilate the wheel assemblies. Some inventors developed after-market fenders with aerodynamic functions such as a venturi to suck the spray inboard so it could condense back into water. There were other kinds of fenders with absorbent treatments on their inner walls to take up the spray from the tires and keep the wind stream from generating spray. Most of these approaches helped to a very limited extent, but when a combination vehicle was studied, it became obvious that the major generator of spray was air turbulence produced by the tractor or nose of the truck, and between the tractor and trailer. The barn door aerodynamics of a cab-over tractor or even conventional cab guaranteed such turbulence, exacerbated by the aerodynamics between the rear of the tractor and the front end of the trailer (depending upon the trailer type). The provision of a fairing ("aero aid") on the roof of the cab to help the airflow flow smoothly down the trailer can result in considerable improvement in spray suppression when teamed with wheel assembly treatments such as full absorbent flaps and skirts.

Late in the decade, the major heavy truck manufacturers at that time all introduced tractors that were engineered to reduce drag and thus increase fuel economy. Such designs also produced dramatic reductions in spray if they were hitched to van type trailers, less so if the trailers had their own aerodynamic problems. Even on low-drag tractors or trucks, it was found that full flaps with absorbent surfaces definitely helped reduce spray cloud density. "Full flaps" means flaps large enough to completely mask the tire or tires from the rear (much larger than flaps generally provided by original equipment manufacturers (OEM).

PURPOSE AND SCOPE OF PROJECT

Since the late 1980s few efforts have been made to identify and test newly developed spray devices. Due to the marked lack of spray product identification and testing since 1990, the primary purpose of the present project was to identify and then examine the utility of devices introduced since 1990 that purport to reduce spray from large trucks. Additional considerations associated with the present project were to identify European Union methodologies to evaluate splash and spray production from large trucks, and to employ an alternative spray testing methodology to determine the similarity of results to the traditionally accepted Laser-Based method.

In light of the multi-purpose nature of the project the four basic research questions posed in this experiment were:

1. When a newer more aerodynamic tractor-trailer combination (the 1997 tractor-trailer) is fitted with spray fenders, is spray and splash suppressed, as measured by the SAE laser-based procedure?

2. When an older less aerodynamic tractor-trailer combination (the 1985 tractor-trailer) is fitted with spray fenders, is spray and splash suppressed, as measured by the SAE laser-based procedure?

3. Is there a difference in splash and spray suppression between the 1997 and 1985 tractors, as measured by the SAE laser-based procedure?

4. How similar are the results of the laser and video-based methodologies?

REVIEW OF LITERATURE

LITERATURE

There is scant published research since the early 1990's on devices for the suppression of spray from large trucks during wet weather. In fact, the examination of spray devices seems to be a byproduct of research on the development and examination of new methodologies for the measurement and analysis of spray production. These new methodologies include the scattered light method, the video-based method, and the PLM16 method. Published research regarding the effectiveness of spray devices is presented in chronological order of publication.

Goetz and Schoch

In 1995, in an attempt to examine the newly developed scattered light methodology for measuring spray production, Goetz and Schoch examined six spray treatments on a truck. Although not specifically identified in the text, depictions indicate the test truck was a straight truck consisting of a steering axle and a rear tandem axle. One treatment tested was a standard fender but without mud flaps at the rear axle. The second treatment tested was a standard fender that had grooved channels on the underside of the fender. The third treatment tested was a standard fender with grooved channels with mud flaps extending to 1.95 inches (50mm) above the road surface. The fourth treatment was a fender with a water absorber. The water absorber consisted of flaps behind each set of tires and between the tandem axle tires. The fifth treatment was a standard fender with air/water separators. The air/water separators consisted of brush at the bottom of the flap and brush around the outer semicircular edge of the fender surrounding each tire. The last spray treatment variation tested was a full fairing. However, the design or configuration of the full fairing was not specified in the text.

Results of the examination are presented in Table 1 and indicated that, when compared to the standard fender without mud flaps at the rear axle, the full fairing treatment produced the least amount of spray. Interestingly, the fenders with water absorbers (the fourth treatment) produced more spray than the standard against which it was compared. Goetz and Schoch indicate this was due to the ability of spray to exit the vehicle at the large gap between the wheel and wheel arch.

Mousley, Watkins, and Seyer

In 1997, Mousley, Watkins, & Seyer presented the results of a study using the video-based method to examine the amount of spray produced by three spray reduction configurations. The first configuration, a baseline, consisted of mud-guards attached to the steering axle and untextured rubber flaps fitted behind all wheels. The second configuration was identical to the baseline configuration except the flaps were

Spray Treatments	**Relative Percent Spray at 37.2 mph (60 kph)**	**Relative Percent Spray at 49.6 mph (80 kph)**
Standard fender without flaps at rear axle	100	100
Standard fender with grooved channels	50	64
Standard fender with grooved channels with long flaps	27	40
Fender with water absorber	107	135
Standard fender with air/water separators	43	75
Full fairing	23	23

Table1. *Results of the 1995 Goetz and Schoch examination of spray devices using the scattered light method. Note, the full fairing treatment produced the least amount of spray by reducing the level of spray by 77% compared to the spray treatment of standard fender without flaps at rear axle.*

replaced with commercially available textured flaps. For the third configuration all mudguards and flaps were removed. Results indicated little variation in the amount of produced spray among the three configurations and, as the author indicated, “no solid conclusions can be made as to which configuration performed best.”

Dumas, Lemay, Bibeau, and Lamontagne

In 1998, Dumas, Lemay, Bibeau, and Lamontagne detailed work done for the Quebec Department of Transport to develop and refine a method for examining spray. This method was earlier referred to as the PLM16. In this work the authors examined six configurations for reducing spray produced by large trucks. Configuration one consisted of Air Fenders (see Figure 1) installed on the tandem axles of the tractor-trailer instead of the OEM equipment. Configuration two was identical to configuration one except that side panels were added to the outside upper level of the steering axle wheel housing. Configuration three was identical to configuration one except the sidewalls of the Air Fenders were removed and the air inlets were blocked. Configuration four consisted of the Reddaway system with no side panels added to the steering axle wheel housing. The Reddaway system can best be described as a wheel fender with flaps ahead and behind the tractor’s tandem axle wheels and a wheel fender with flaps between and behind the van-trailer’s tandem axle. This system also included side panels added to the outside upper level of each of the tandem axles. Configuration five was identical to configuration four except that side panels were added to the outside of the upper level of the steering axle wheel housing. Configuration six consisted of the basic tractor-trailer with fenders fitted over each tandem axle wheel set. Note, there were no side panels added to the outside of each wheel housing.

Results were presented as an opacity index that indicated the amount of spray generated. In general, results indicated the average of the Air Fender system decreased opacity (produced less spray) near the truck up to about six feet (1.83 m) as compared to the average of the Reddaway systems tested, after six feet the Reddaway system produced less spray. Broken down by configuration and distance from the test track, 48 inches (121.92 cm) from the test track configuration one produced the least amount of spray (45%) and at 96 and 144 inches (243.84 and 365.76 cm) configuration two produced the least amount of spray (35% and 25% respectively).

NHTSA Report to Congress

NHTSA concluded in 1988 that available splash and spray suppression technologies were not effective and therefore trucks were not required to install the suppression devices. Nevertheless, due to large numbers of complaints by motorists and pressure from Congress, truck splash and spray remains a concern of the National Highway Traffic Safety Administration. NHTSA's March 2000 Report to Congress (2000) reviewed recent literature and crash data and concluded that although splash and spray does not appear to cause a large number of crashes, it's still a serious problem from the perspective of many drivers. The report also mentioned possible underreporting of splash and spray related crashes.

DEVICES FOR REDUCING SPLASH AND SPRAY

Since the early 1960's, devices have been developed that can be attached to tractor-trailer or tractor flatbed-trailer combinations to reduce spray produced in wet weather conditions. Many of the more promising devices available commercially before 1990 were identified and tested (Koppa, 1984; Koppa, 1989; Koppa & Pendleton, 1987; Koppa & Pendleton, 1987; Koppa & Pendleton, 1987; Koppa & Pendleton, 1987; Koppa, Pendleton, & Zimmer, 1986; Koppa, Pendleton, Zimmer, Pezoldt, & Bremer, 1985; Koppa, Pezoldt, 1988; Koppa, Pezoldt, 1988; Koppa, Pezoldt, Gonzales, & Pendleton, 1988; Koppa, Zimmer, Ivey, & Pendleton, 1984; Pendleton, Koppa, & Gonzalez-Vega, 1988; Wright, Koppa, Huchingson, & Johnston, 1990). For consideration in the current project a spray device is an OEM or aftermarket product, a product that is designed for and can be attached to either a tractor-trailer or a tractor flatbed-trailer combination, is a product that is available commercially or is in the prototype stage, and a product or prototype that has been or has become available or in the prototype stage since 1990.

On-Line Searches and Contacts

To identify viable spray devices several searches were performed in available online databases to identify potential sources of spray devices. These databases included the American Trucking Association database, the European Patent Office database, the United States Department of Transportation DOTBOT database, the United States Federal Highway Administration (FHWA) DOTBOT database, the United States National Highway and Traffic Safety Administration (NHTSA) DOTBOT database, the

United States Patent and Trademark office database, and the world wide web. A literature search examining over 12,600 journals was performed employing the First Search© Internet database. The specific keyword search terms used for all searches are presented in Appendix A. In addition, a variety of sources including AAA Foundation for Traffic Safety, Federal Highways Administration, National Highway Traffic Safety Administration, U.S. and European truck manufacturers, U.S. and European truck equipment manufacturers, the U.S. Trademark and Patent Office, and prominent personnel in the field of spray suppression devices were contacted. These contacts were in the form of phone conversations, short briefings, and/or email on the nature of this research project.

Identification of Spray Devices

These searches and contacts resulted in a list of products, companies, and patent holders who have been active in the development of spray devices for large trucks since 1990. The results of these searches are presented in Appendix B. An effort was made to contact each of these companies or individuals via available on-line sources, phone, email, or fax. Companies or individuals were then asked to provide an overview of spray activities in which they have been involved in the last ten years and to provide a description of any commercially available spray devices they may offer. Of the 22 companies and individuals identified in the searches, only a handful offered products that purported to reduce spray for large trucks. It should be noted that one reason for the paucity of products is that truck companies have determined that devices which stop or ‘catch’ spray after it has been produced are not nearly as successful as preventing spray production in the first place, through better aerodynamic tractor designs. Many companies are focusing on improving tractor aerodynamics.

Companies producing spray products include Air Fender Systems, James Clutter, DynaPlas Pty. Ltd., Fleet Engineers Incorporated, Freightliner Corporation, Mercedes, Schlegel Systems Incorporated, Symplastics Incorporated, and Pekka Turunen. A description of each of their primary spray products is offered below. There are several companies that produce spray reduction devices that are not listed because those devices are variations on the devices included here.

Air Fender Systems Incorporated, headquartered in Cartersville Georgia, offers a spray system that consists of a fender outfitted with a series of air inlets located on the front and side of the fender. This system is a departure from standard spray reduction fenders because of the air inlets. See Figure 1 for a depiction of the Air Fender.

Figure 1. *A depiction of the Air Fender Systems Incorporated fender.*

James Clutter, formerly the CEO of JECO Plastics located in Plainfield, Indiana, has a prototype spray reduction device, the RainDowner, which is a double layer fender. The double layer system is unique in that it can "trap" splash and spray, channel it to the front or rear edge of the fender, and deposit it on the ground. See Figure 2 for a depiction of the RainDowner.

Figure 2. *A depiction of the Raindowner fender.*

Dynaplas Pty. Limited, located in Sydney Australia, offered a variety of full wheel mudguards and a spray suppressant kit (see Figure 3). This spray suppressant kit represents a combination of polypropylene filament ordered in varying lengths that can be custom cut to any width. The system's unique feature is the combination of mudflaps and filament to reduce splash and spray production.

Figure 3. *A depiction of the Dynaplas Pty. Limited full wheel mudguards and spray suppressant kit.*

Fleet Engineers Incorporated, located in Muskegon Michigan, offers mudflaps, wheel wells, and polypropylene filament. However, Fleet Engineers' most promising spray device is the Spray Mate Polypropylene Fender outfitted with the Spray Mate Curved Brush Kit (see Figure 4). The Spray Mate Polypropylene Fender features consist of a polypropylene wheel well with vertical ribs molded to the inner surface to add strength and splash and spray reduction. The Spray Mate Curved Brush Kit consists of polypropylene filament that can be mounted on the curved outside edge of the Spray Mate Polypropylene Fender.

Figure 4. *A depiction of the Fleet Engineers Incorporated Spray Mate polypropylene Fender outfitted with the Spray Mate Curved Brush Kit.*

Schlegel Systems Incorporated, based in Rochester New York, offers the 20/20 suppressant, a polypropylene filament of varying lengths and widths that can be attached to both straight and curved surfaces of tractors and trailers. See Figure 5 for a depiction of the 20/20 suppressant. This system and close variants of this system are not new and have been commercially available for quite some time.

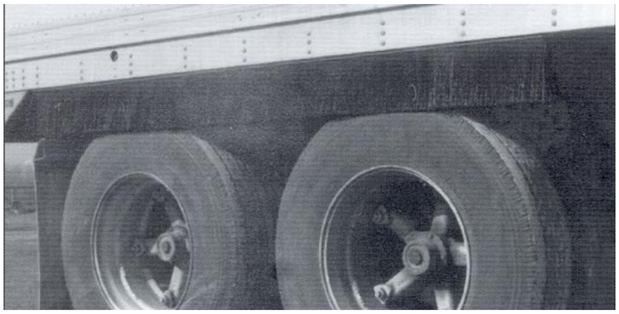

Figure 5. *A depiction of the Schlegel Systems Incorporated 20/20 Suppressant. Note, the 20/20 Suppressant is generally fitted to the entire length of each outside lower edge of a van-trailer.*

Symplastics Limited, located in St. Peters Missouri, produces the Poly Guard Plus™ Anti Spray Flap that uniquely combines artificial grass mounted on a sturdy polyethylene backing (see Figure 6).

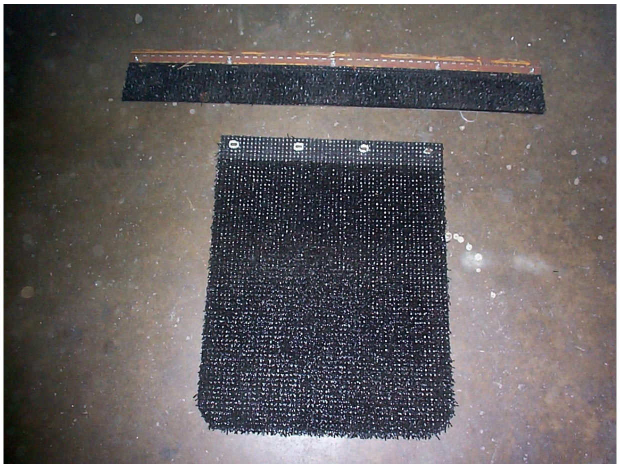

Figure 6. *A depiction of the Symplastics Limited Poly Guard Plus' Anti Spray Flap. Note, the Poly Guard Plus' Anti Spray Flap is generally fitted to each pair of wheels on tractors and to the entire length of each outside lower edge of a van-trailer.*

Pekka Turunen, an inventor located in Helsinki Finland, offers the Antispray® spray guard (see Figure 7). The device is mounted in the fender-wells of trucks to replace standard mud flaps. The unique feature of this device is several vertical guiding surfaces intended to redirect and then deposit spray on the ground.

MEASUREMENT TOOLS

Figure 7. *A depiction of the Antispray(r) spray guard offered by Pekka Turunen in Finland.*

The testing protocols for measuring spray from trucks have evolved from subjective estimates by observers on the highway or viewing filmed records, to wind tunnel approaches for evaluating individual wheel or axle treatments. There now exist several methods for measuring splash and spray produced by large trucks. A summary of each of these methods is provided below in chronological order of their publication.

European Union Method

In March of 1991 the Council of European Communities adopted laboratory procedures for testing spray devices. According to the Official Journal of the European Communities (1991) "The aim of this test is to quantify the ability of a device to retain the water directed against it by a series of jets. The test assembly is intended to reproduce the conditions under which the device is to function when fitted to a vehicle as regards the volume and speed of the water thrown up from the ground by the tyre tread". The test setup consists of placing a sample of a spray device a short distance away from a high-pressure spray nozzle. A measured amount of water is emitted from the nozzle and projected to the spray device. A tray placed below the device collects and measures the amount of water retained and dropped. To successfully pass the test 70% and 85% of the water must be collected from the initial amount emitted for energy absorbing and air/water separator type spray devices, respectively.

SAE J2245 Digitizing Method

The digitizing method is similar to the laser method except that each side of the test pad is flanked by a high-resolution, black and white camera located 150 feet (45.72 m) from the leading edge of the test pad. Each camera films a 12 feet wide (3.66 m) x 8 feet (2.44 m) tall board on each side of the test pad which is located 350 feet (106.68 m) from the leading edge. The face of each board is painted with one foot square black and white squares. The cloud of spray is measured by determining the change in contrast between control images (with no splash and spray) and the test images (with spray). Similar to the J2245 laser method, eight test runs are performed in eight different wind conditions.

An advantage of the digitizing method is that a large portion of the spray cloud is filmed and digitized which allows for an inspection of the formation of the shape and size of the spray cloud over time. However, the digitizing method has been studied and it was found that it gave equivalent (highly correlated) measures to those obtained using the SAE J2245 laser method (Koppa et al., 1990).

Mercedes Benz Scattered Light Method

In an effort to examine the amount of spray produced by large and small vehicles in an ecologically valid manner researchers at Mercedes Benz developed, what will be termed here, the 'Mercedes Benz Scattered Light' method (Goetz & Schoch, 1995). The scattered light method consists of two primary components: 1) a light source, placed above and to the side of a vehicle, which produces a light curtain directed at the ground and 2) a light detector which is placed near the bottom and to the same side of the vehicle as the light source. As a vehicle drives over wet pavement at 37.2 mph (60 kph) and 49.6 mph (80 kph), water droplets that are emitted from the wheel arch, flow through the light curtain and reflect light. As more and more water flows though the light curtain more and more light is reflected and less light registered by the light detector. Advantages of the scattered light method are that the components can be fixed behind a variety of vehicles including large trucks and that there is little or no interference from other light sources. However, this latter advantage is negligible as experimental runs can only be performed at night or in dim daylight.

PLM16

Recently, a project was undertaken to develop a system for measuring spray that would evaluate the transverse dimensions of a spray cloud, evaluate the longitudinal density of the spray cloud, prove to be reliable, and would be reasonable in cost and complexity (Dumas, Lemay, Bibeau, & Lamontagne, 1998). The system is a variant of the SAE J2245 laser method and for the present purposes will be identified as PLM16 (photo/laser, 16 photodiodes method). The PLM16 testpad consisted of a 1200 foot (365.76 m) zone, in which the truck obtained a criterion speed of 48 mph (77 kph), a 100 foot (30.48 m) wet zone, and then a 200 foot (60.96 m) wetted test zone. The criterion depth of water across the central 100 foot (30.48 m) span of the 200 foot (60.96 m) wetted test zone was 3/64 inch (1 mm). Located at the front of the 200 foot (60.96 m) wetted test zone, next to and perpendicular to the test pad, were 16 photodiode detector assemblies placed next to each other in a line. The entire assembly extended 16 feet (4.88 m) away from the edge of the test pad. All 16 photodiode detector assemblies were aimed at a single laser apparatus. The laser apparatus was placed at the end of the 200 foot (60.96 m) wetted test zone, immediately next to the test pad and on the same side as the photodiode detectors. The laser apparatus is a 'horizontal scanning beam' that consists of a laser beam being projected onto an oscillating mirror. The oscillating mirror system redirects the laser beam through a plane over a specified area many times a second. The horizontal scanning beam is analogous to the repetitive beam of light projected by a lighthouse. As the laser beam moves across the plane it intersects each of the 16 photodiode detector assemblies exciting each of the photodiode detector assemblies.

Similar to J2245 laser method, the spray produced by large trucks is measured by the laser system as a reduced level of light passing between the horizontal scanning beam and the photodiode detectors and is referred to as an opacity index. The principle advantage of the PLM16 over the J2245 laser method is that data from a total of 16 lateral positions ranging from about 30 to 180 inches (76.3 to 457.2 cm) can be collected to provide a depiction of the spray cloud produced by large trucks in wet weather conditions.

Video-Based Method

Recently, a variant of the J2245 digitizing method has been presented by Mousley, Watkins, & Seyer (1997). The primary difference between the video-based and digitizing methods is that 100 frames of video are collected at 12.5 frames per second versus four frames of video collected at 30 frames per second, respectively. This new data collection configuration, a result of advances in video-based technology since initial development of the digitization method, results in a longer period of time over which to collect and average data. For a complete presentation of the Video-Based methodology please see Video-Based Methodology later in this report.

SAE J2245 Laser Method

At present the most widely recognized and accepted method for measuring spray in the United States is the Surface Vehicle Recommended Practice J2245 of the SAE (1994). Although a full review of J2245 is encouraged, a short summary will be provided here. SAE J2245 recommends a test setup of a 400 foot (121.92 m) long by 12 foot (3.66 m) wide testpad consisting of typical highway asphalt covered with water to a depth of .02 to .05 inch (.51 to 1.27 mm). 175 feet (53.34 m) from the leading edge, each side of the testpad is flanked by two laser transmitters sending out a beam of light to laser receptors located 225 feet (68.58 m) from the leading edge. The test procedure recommended by SAE J2245 employs a test vehicle, one commonly operated on a highway (e.g., a tractor-trailer), driven across the testpad at a speed of 55 mph (88.5 kph). As the test vehicle travels across the test pad it creates a 'cloud' of spray. The spray is measured by the laser system as a reduced level of light passing between the laser transmitters and receptors. The reduced level of light is expressed as a percentage of the maximum possible light transmitted during a calibration performed immediately before a test run. Eight test runs are performed in eight different wind conditions. For a complete presentation of the SAE J2245 laser methodology please see Experiment One Methodology later in this report.

Due to the lack of empirical data on the effectiveness of the various devices to reduce spray, the purpose of the present investigation was, in accordance with SAE J2245, to determine which devices, in fact, reduce spray on two different large trucks during wet weather. In addition, a tertiary purpose was to determine how similar the results of a more recently refined testing methodology (video-based methodology) would compare with the SAE J2245 methodology (laser-based methodology).

METHODS

LASER-BASED PROTOCOL

As part of this evaluation of spray devices, TTI conducted a limited series of tests of existing or prototype products purporting to reduce splash and spray from large trucks employing the SAE J2245 Laser Method. The SAE J2245 Laser Method was employed because it has proved to be one of the most valid and reliable testing protocols available for spray device testing. In conjunction with the AAA Foundation for Traffic Safety several devices that purported to suppress spray from large trucks were identified, pilot tested, and then fully tested. These devices were selected because they purport to reduce splash and spray from large trucks, are currently offered by companies or are in the prototype stage of development, or are representative of a class of splash and spray reduction devices.

Experimental Setup

Test Pad Setup

The test setup was located at the Riverside Campus of Texas A&M University just west of Bryan, Texas. A 475 ft x 20 ft (144.78 x 6.096 m) strip of special asphalt concrete has been built at the Riverside Campus for splash and spray testing. This pad has been used since 1984 and forms the basis for the specifications in SAE J2245.

The pad was equipped with a two inch (5.08 cm) PVC pipe perforated with holes at six inch (15.24 cm) intervals along its entire length (see Figure 8). The pipe was served by a nearby hydrant that could have supplied a continuous stream of water in excess of 50,000 gallons (193,700 liters) per day, but was regulated by a set of valves to cover the test pad surface to a depth of between 0.02 and .05 inch (.51 and 1.27 mm).

Figure 8. *Depiction of the 2 inch (5.08 cm) PVC pipe perforated with holes at six inch (15.24 cm) intervals.*

Apparatus

The pad was flanked by four solid-state Optima DLM 3604-650 Diode Laser Modules (see Figure 9) and four Metrologic Photometer laser photocell receivers (see Figure 10) with Texas Transportation Institute designed optics which served to measure the density of spray produced by the test vehicles. These devices work on the same principle as fog detectors at airports or along mountain roads. A laser beam excites a photocell on the receiver; the voltage output of the photosensitive device is directly proportional to the energy delivered by the laser beam. Any substance that intrudes into that beam scatters the beam and reduces its incident energy. In order to control for ambient light conditions, the output of the photocell was calibrated prior to each test run, by shutting off the beam (0 per cent) and then turning it back on (100 per cent). Each transmissometer was calibrated with a standard 25% and 75% neutral filter lens. The distance between the laser source and photocell was 50 ft (15.24 m); at that distance, the beam spreads enough to subtend an angle larger than the photocell surface. To correct for this, a collector lens was used to focus all the incident light to a sharp point on the photocell surface. The lasers employed did not require an external shutter for calibration. The transmissometers were mounted on sturdy brackets secured to the pavement at the locations specified in J2245. They delivered at least 4 mW/cm^2. The pad instrumentation also included a Young anemometer (model 05103V), an Omega temperature sensor (model 199) with a type J thermocouple, and an Immac relative humidity gauge.

Figure 9. *A depiction of one of the four solid-state lasers in a protective housing.*

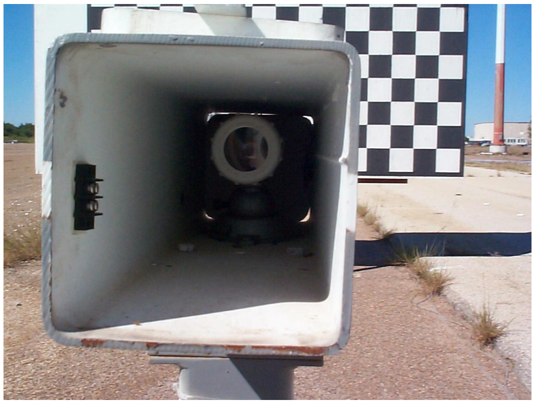

Figure 10. *A depiction of one of the four solid-state laser receivers in a protective housing.*

The test instrumentation was connected via a standard 486 DX4 100 Mhz computer (400 megabyte hard drive and 16 megabyte random access memory) located in a test shelter adjacent to the test pad. A data acquisition program written at TTI was used on this computer. Information was automatically recorded in a data file for each run at a sampling rate of 25 samples a second. Data collected for each run included: date and time of test run, transmissometer readings (4), wind speed, and wind direction. Manual input parameters included test run number, relative humidity, temperature, and truck speed. Truck speed was measured using a Kustom (model KR-11) radar gun.

For additional documentation, video footage of all runs was captured with a Pelco closed circuit video camera, displayed on a Sanyo VM4509 Video Monitor, and recorded onto VHS video tape via a HQ XR-1000 video cassette recorder. Superimposed on the video footage was wind direction, wind speed, and minimum transmissometer measurements. For an illustration of the testpad setup see Figure 11.

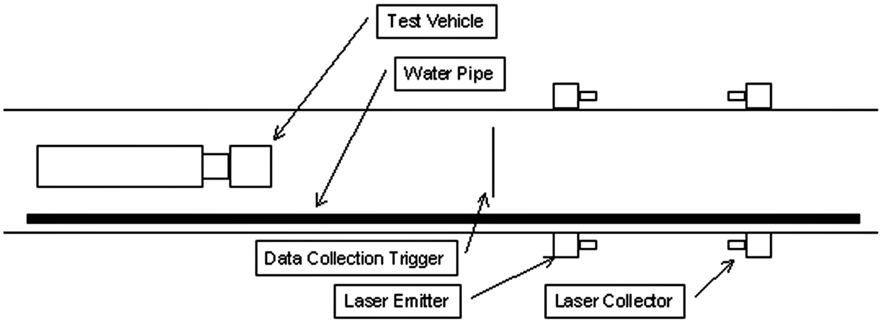

Figure 11. *A schematic of the layout of the laser data collection method.*

1985 Tractor, 1997 Tractor, and Van-Trailer

One of the two tractors used for testing was a 1985 Freightliner, model number C120064ST, manufactured in October 1985 and owned by TTI. The tractor had a single front steering axle (an FF-941 Rockwell) and a tandem rear axle. Tread depth averaged 3/8 inch (9.53 mm). See Figure 12 for a depiction of the tractor.

Figure 12. *1985 Freightliner tractor and van trailer used for testing splash and spray devices. Note, the trailer connected to the tractor in this figure was not used for testing.*

The second tractor was a 1997 Freightliner Century Class S/T tractor kindly provided by its manufacturer. The tractor had a single front steering axle and a tandem rear axle. Tread depth was 3/8 inch (9.53 mm). See Figure 13 for a depiction of the tractor.

Figure 13. *1997 Freightliner Century Class tractor and van trailer used for test runs.*

Both tractors were equipped with aerodynamic fairings. The van-trailer used for all testing was manufactured by Trailmobile Incorporated in August 1984, and had tandem rear axles, a coupler height of 47.5 inches (120.65 cm), and was 162 inches (411.48 cm) in height, 96 inches (243.84 cm) wide, and 48 feet (14.63 m) in length. The tires on the van-trailer were 11r 22.5 G with a tread depth of at least 3/4 inch (1.91 cm) mounted on 8.25 x 22.5 inch (20.96 x 35.40 cm) steel rims.

Wind Categories

A variety of wind categories were employed to identify the device that reduced the production of spray the most. The four different wind direction/speed conditions were slowwinds (0 - 3 mph wind) (0 – 4.83 kph) in any wind direction, tailwind (3 - 10 mph wind) (0 – 4.83 kph), right crosswind (3 - 10 mph wind) (4.83 – 16.09 kph), and left crosswind (3 - 10 mph wind) (4.83 – 16.09 kph). Relative to the front of each tractor-trailer configuration tailwinds were between 170 and 190 degrees, left crosswinds were between 191-349 degrees, and right crosswinds were between 11-169 degrees. Due to the inconsistent presentation of headwinds (350 –10 degrees) in weather patterns at the test pad throughout the period of data collection this wind direction was not employed.

Pilot Test Runs

The purpose of pilot testing was to identify through limited testing the single device that reduced the production of spray the most. The device that reduced the production of spray the greatest would then be employed in complete protocol test runs. Devices where chosen for pilot testing because they were developed or markedly changed since 1990.

Five devices that purported to reduce spray for large trucks during wet weather conditions and a baseline condition were pilot tested. All pilot test configurations consisted of the 1985 Freightliner tractor pulling the same Trailmobile van-trailer. Each configuration is detailed below.

- Pilot Configuration Baseline consisted of standard OEM spray reduction flaps behind each wheel. The spray reduction flaps were solid rubber with no artificial grass or grooves. This configuration was pilot tested because it is commonly added to new tractor-trailers as part of the OEM spray reduction and mud flap system. In addition, it is commonly found on many new and existing tractor-trailers in use today.

- Pilot Configuration One consisted of OEM spray reduction flaps on the steering axle of the tractor and commercially available spray reduction fenders mounted on the tandem axles of the tractor and van-trailer. This configuration was pilot tested because it is commonly marketed and found on many new and existing tractor-trailers in use today and represents the general class of spray reduction fenders and their typical application.

- Pilot Configuration Two consisted of OEM spray reduction flaps on the steering axle of the tractor and commercially available spray reduction fenders, with brush along the outside edge of the fender, mounted on the tandem axles of tractor and van-trailer. This configuration was pilot tested because it is commonly marketed as an aftermarket splash and spray reduction device and is found on many existing tractor-trailers in use today and represents the general class of spray reduction devices that combine the use of fenders and spray reduction brush around a wheel.

- Pilot Configuration Three consisted of OEM spray reduction flaps on the steering axle of the tractor and spray reduction fenders on the tandem axles of the tractor and van-trailer. These fenders were different than the previous two fender conditions in that fore and aft sections of the fenders extended to within several inches of the track surface. It was not practical to mount these fenders to the steering axle of the tractor due to the nature and amount of modifications to the cab of the tractor. This device was tested because it represented a slightly modified design of the traditional fender splash and spray reduction system.

- Pilot Configuration Four was identical to Pilot Configuration Baseline except that 6 inch (15.24 cm) long brush 48 inches (121.92 cm) wide was attached to the tandem axles of the tractor and van-trailer. This configuration was pilot tested because it is commonly marketed and found on many new and existing tractor-trailers in use today and represents the general class of spray reduction brush and their typical application.

- Pilot Configuration Five consisted of material similar to artificial grass placed on a solid plastic flap located behind each wheel and identical material 8 inches (20.32 cm) long attached to the entire outside lower edge of the van-trailer. This configuration was pilot tested because it is commonly marketed and represents the general class of products that employ artificial grass mounted on a solid plastic flap.

In general, none of the devices represent a significant change in product design beyond what has been tested in previous studies. The availability of the product for testing was the main consideration for inclusion in pilot testing.

Pilot testing consisted of performing 8 runs in a right crosswind (3 - 10 mph) (4.83 – 16.09 kph) condition at 55 mph (88.5 kph) for each configuration and the pilot baseline configuration. Right crosswinds were chosen for two reasons: first, right crosswinds represents a more stringent wind condition than slowwinds or tailwinds; and, two, right crosswinds are the most prevalent wind condition at the test facility.

Since the spray protocol calls for the test of a complete vehicle, each device maker supplied a complete spray suppression system for an entire vehicle. TTI arranged for the provision of the vehicle required; it was assumed that device makers would furnish prototypes or production versions of their devices for testing at their cost. Data on the performance of their devices was made available to their manufacturers. Where necessary, provisions were made to protect proprietary interests of the various makers, consistent with the goals of the project and desires of the AAA Foundation for Traffic Safety.

55 MPH Complete Protocol Test Runs

The purpose of complete protocol testing was to determine if any one of four spray reduction configurations reduced the amount of spray produced by the two large test trucks (the four spray reduction configurations are presented later in this section), to determine whether the spray treatment was effective at a variety of vehicle speeds, and to determine the role of vehicle aerodynamics in the distribution of spray. The device that reduced spray to the greatest extent in pilot testing was used for the 55 mph (88.5 kph) complete protocol test runs.

Complete protocol testing consisted of examining four different tractor-trailer configurations at 55 mph (88.5 kph) using two different tractor-trailers. Eight test runs were performed in each of four different wind direction/speed conditions for each of the four different splash and spray configurations. The four different wind direction/speed conditions were slowwinds, tailwinds, right crosswind, and left crosswind. Each configuration is detailed below.

- Configuration One consisted of the 1997 tractor-trailer combination outfitted with OEM flaps. The OEM spray reduction flaps were solid rubber with no artificial grass or grooves.

- Configuration Two consisted of the 1997 tractor-trailer combination outfitted with the most effective spray device identified through pilot testing (pilot configuration three). The steering axle and the tandem axle of the tractor were outfitted with OEM flaps (the spray reduction flaps were solid rubber with no artificial grass or grooves) while the tandem axle of the van-trailer was outfitted with the spray device. Note, it was not practical to mount these fenders to the steering or tandem axle of the tractor due to the nature and amount of modifications to the cab of the tractor.

- Configuration Three consisted of the 1985 tractor-trailer with no spray devices other than OEM flaps (this configuration is identical to the Baseline Configuration for Pilot testing).

- Configuration Four consisted of the 1985 tractor-trailer configuration outfitted with the most effective spray device identified through pilot testing (pilot configuration three). OEM spray reduction flaps were affixed to the steering axle of the tractor and the spray reduction fenders were affixed to the tandem axles of the tractor and van-trailer. The spray reduction flaps were solid rubber with no artificial grass or grooves. Again, it was not practical to mount these fenders to the steering axle of the tractor due to the nature and amount of modifications to the cab of the tractor.

Compared to the 1985 tractor, the design of the 1997 tractor is one that represents markedly improved aerodynamics due to specially designed aero-aids on the top of the tractor, side of the tractor, and around the fuel cells of the tractor.

65 MPH Complete Protocol Test Runs

Complete protocol testing also included the examination of the four tractor-trailer configurations at 65 mph. Again, eight test runs were performed in each of four different wind direction/speed conditions for each of the four different spray configurations.

Since spray evaluation is comparative rather than absolute, it was desirable to have two “no treatment” baseline tractor-trailer configurations to determine the magnitude of effect for a particular device and the influence of tractor aerodynamics. These were Configuration One (the 1997 tractor-trailer outfitted with OEM flaps) and Configuration Three (the 1985 tractor-trailer outfitted with OEM flaps). The test plan followed SAE J2245 paragraphs 6.2, 6.3.2, 6.4, 6.4.2.

The test crew for all runs consisted of a test conductor, truck driver, safety/test pad technician, shop personnel to help with configuration changes, and a technician to collect data using the video-based data collection method. The safety/testpad technician was seated in a TTI vehicle equipped with a rotating beacon, in radio contact with the test conductor and the truck driver. If any traffic strayed anywhere near the test location or the path of the truck, notification from the safety/testpad technician led to halting the run.

Statistical Analysis

The basic unit of measure for the Laser-Based protocol was the percentage transmittance. The percentage transmittance essentially represents the amount of laser light measured for a single trial. As indicated earlier to control for ambient light conditions, the output of the photocell was calibrated prior to each test run, by shutting off the beam (0 per cent) and then turning it back on to measure light transmittance. When the laser was turned back on this represented light transmittance of 100%. Percent transmittance for each of the four lasers was then generated by calculating the maximum amount of reduction of laser light, as compared to the calibration, when the tractor-trailer traveled along the wet test pad. For example, a percent transmittance of 70% would indicate 70% of the light transmitted by the laser was received by the photocells and 30% was blocked by splash and spray.

Two or four percentages of transmittance (the data from either two or four lasers) were then averaged to generate a Figure of Merit (FOM). Data reduction to a Figure of Merit employed in the statistical analysis for the Laser-Based methodology followed the procedures outlined in SAE J2245 paragraphs 7.2 and 7.3 which will be described here briefly. The data acquisition program automatically provided percent transmittance (or as specified in SAE J2245, 100 - percent transmittance = % obscured). Then the SAE J2245 Downwind Rule was invoked to derive the final FOM for a given test run. The Downwind Rule indicates “wind speed and direction can effectively move all the spray to one side of the truck. In high-crosswind conditions, the following conservative approach shall be taken: use the average FOM from the downwind side of the truck as the overall FOM, instead of the average.” In this example of high-crosswind conditions the two measures of percent transmittance (one measure for each laser) of the two lasers on the downwind side of the test track were then averaged to arrive at a FOM for that particular trial. If during the trial the winds were either headwind or tailwind conditions the four measures of percent transmittance (one measure for each of the four lasers) were then averaged to arrive at a FOM for that particular trial. The FOM was then used in all statistical analysis.

Pilot test runs were analyzed using a univariate analysis of variance with spray treatment (6) as the independent variable and FOM as the dependent variable. The basic question is which device, if any, reduces the production of splash and spray to the greatest degree on the 1985 tractor-trailer combination.

For full protocol testing the data were evaluated using analysis of variance (ANOVA) procedures. Three-way fixed effects models (two levels of speed, four levels of wind, and four levels of vehicle configuration) were fitted to the data. Checks were run to see if any first-order interactions of the three main effects added significantly to the predictive power of simple main-effects models. Three basic questions were asked in the experiment:

1. When the 1997 tractor is fitted with spray fenders, is spray and splash sup-

pressed, i.e., are vehicle configurations one and two different?

2. When the 1985 tractor is fitted with spray fenders, is spray and splash suppressed, i.e., are vehicle configurations three and four different?
3. Is there a difference is splash and spray suppression between the 1997 and 1985 tractors, i.e., are vehicle configurations one and two different from vehicle configurations three and four?

Statistical Analysis Conceptualization and Background

The data from this study and the second study were analyzed in a traditional ANOVA fashion as described in each of the Statistical Analysis sections and the Results sections for both the laser and video based methodologies. However, it has been suggested that these data should have been analyzed via a repeated measures design. To address this concern a more complete explanation is provided regarding 'why' the data were collected and analyzed using the design identified.

This experiment as originally conceptualized included 32 experimental situations: two speeds by four wind conditions by four vehicle configurations. The two speeds were 55 and 65 mph while the four wind conditions were; no wind, 3-10 mph tail wind, 3-10 mph left cross wind, and 3-10 mph right cross wind. When any other wind condition was obtained, the experiment was not run. Of paramount importance is the fact that two tractors (a 1985 model and a 1997 model) were available and used in this study. These tractors were equipped or not equipped with original equipment manufacturer flaps and spray fenders. The flaps and fenders used on the 1985 and 1997 model tractor-trailers were basically the same, but altered somewhat to fit truck tractors from two different model years. Thus, the four vehicle configurations were as follows:

1. 1997 Tractor, OEM Flaps and no Spray Fenders
2. 1997 Tractor, OEM Flaps and Spray Fenders
3. 1985 Tractor, OEM Flaps and no Spray Fenders
4. 1985 Tractor, OEM Flaps and Spray Fenders

For each of the 32 experimental situations, eight data points were collected. That is to say, eight separate runs were made under each of the 32 experimental situations. The 1985 tractor and the 1997 tractor each were used in 128 runs for a total of 256 data points. Half the runs for each year tractor-trailer were completed with no OEM flaps and spray fenders and another half were completed with spray fenders. The same driver was used for all 256 runs in the experiment. This was not the first splash-and-spray experiment in which the driver participated. The driver had been involved in other splash-and-spray experiments over the years.

Traditional ANOVA Design

It should be acknowledged that the use of 32 tractor trailers for this experiment would have been preferred (16 from model year 1985 and 16 from model year 1997), however, the cost of acquiring and modifying all of these tractors would have been prohibitive. As a practical matter, only two truck tractors were employed. See Appendix G for a description of two variations of a hypothetical repeated measures design for this experiment.

In the analyses performed, 32 experimental situations were defined based on speed (2), wind condition (4), and vehicle configuration (4). For each of these 32 situations, eight runs were made. To the extent that different runs (within a given experimental situation) yielded different results, those differences are seen to reflect slight differences in physical conditions from run to run. For example, the driver attempted to drive at exactly 55 or 65 mph, but there were slight variations in this nominal speed from run to run. Crosswinds were acceptable from 3 to 10 mph. However, on one run the wind might have been 4 mph and on the next 8 mph. Every attempt was made to hold surface water depth constant, but minor fluctuations might be expected from run to run. In short, some variance in the eight runs recorded for a given experimental situation would be expected for the physical reasons just listed. Furthermore, this run-to-run variance is not seen to result from sequencing or repetitions, rather, an individual run within a given experimental situation is seen to be independent of other runs in the same sequence.

Because eight runs were carried out for each of the 32 experimental situations in this experiment, an argument can be made that the eight runs were not eight independent measures of the same phenomenon, but were eight, repeated measures of the same phenomenon—in effect, eight different dependent measures. Although that argument is understood, given the practical realities of the experiment, it was thought it was more reasonable to assume that the eight runs in a given experimental situation were, for all intents and purposes, eight independent measures of the same phenomenon. However, it should be acknowledged that had the eight measures recorded within a given experimental situation been derived not from one tractor making eight runs, but from eight tractors each making one run, the variability of recorded measures within experimental situations may very well have been larger.

Note too, the wind was a major obstacle to be overcome in conducting this experiment. If winds were consistent all eight runs for a given experimental situation may have been run consecutively and within a relatively brief period of time. However, when the wind changed from one experimental condition to another, data collection shifted accordingly. Thus, the eight runs that were planned for each experimental situation were not necessarily carried out on the same day such that one or two runs may have been recorded on one day and the balance on the next day. When the wind did not meet any of the four experimental conditions, data could not be collected. In short, the sequencing of test runs was determined by the winds. Given these realities, even if we wanted to analyze the collected data as eight repeated measures for each of 32 different situations, we would have to acknowledge that temporal spacing between successive runs was not constant and not controlled.

If we were to consider the two tractor trailers employed in this study as the “subjects” in the experiment, then repeated measures (i.e., 8 runs) were collected for both subjects under each of 16 discrete experimental situations, i.e., 128 measurements per tractor-trailer. Given this reality, a correct repeated measures analysis cannot be performed. We do not have enough degrees of freedom. There are not enough subjects. Speed, wind, and treatment (fenders/no fenders) are all repeated measures factors even if only one run were made under each of the 16 experimental situations (2 speed conditions by 4 wind conditions by 2 treatment conditions). These 16 measures could all be classified as repeated measures from one subject, i.e., one tractor-trailer.

With regard to our analyses, we recognize that by collecting eight repeated measures with the same tractor trailer, rather than collecting eight measures with eight different tractor trailers, we may have, in effect, held down on the variance in our problem, reduced the size of the error term, and made “statistical significance” relatively easier to achieve. Under ordinary circumstances, it is just this sort of difficulty that would recommend a repeated measures design over a somewhat contrived factorial design.

We also recognize that because only two tractor-trailers were used throughout this experiment (one from model year 1985 and one from model year 1997), any claims that splash and spray suppression differed across model year should be made with caution. In the analysis performed, any “model year effect” that was found may have resulted from unique characteristics of the particular 1985 tractor and/or the particular 1997 tractor employed in the study.

VIDEO-BASED PROTOCOL

As part of this evaluation, TTI simultaneously employed the Video-Based spray testing methodology. This system was similar to the video methodology described in SAE J2245 but included several variations that were developed at the Royal Melbourne Institute of Technology (RMIT), Australia. Details of the differences between the RMIT system and the video-based system described in SAE J2245 can be found in Mousley et al, 1997.

Using two video cameras (one on each side of the track), the video-based system recorded and analyzed the spray alongside a truck as it passed through the wetted test section. The video cameras were focused on two large, black-and-white checkerboards at the far end of the track. As the truck passed through the wetted section spray would pass between the cameras and the checkerboards, partially obscuring the checkerboards from the cameras. This is representative of what occurs when a motorist is following a truck in wet weather. Images of the spray obscuring the checkerboards was then analyzed to quantify the spray and to estimate if a motorist could safely see through the spray produced by the truck.

The main measure of the quantity of spray with the video system was 'Average Percentage Contrast', or APC. Contrast is a measure of the ease with which different objects can be differentiated. If the contrast is low then the two objects cannot be differentiated as they have little contrast to each other. Alternatively, if the contrast between two objects is high, they can clearly be distinguished. APC is the average contrast of the squares on the checkerboards as observed by the video cameras, measured as a percentage of the contrast without any spray. Therefore, an APC of 0% indicates nothing can be seen through the spray while an APC of 100% means there is no spray to obscure vision.

As with experiment one the four basic questions posed in this experiment were:

1. When a newer more aerodynamic tractor-trailer combination (the 1997 tractor-trailer) is fitted with spray fenders, is spray and splash suppressed, as measured by the Video-Based spray testing procedure?

2. When an older less aerodynamic tractor-trailer combination (the 1985 tractor-trailer) is fitted with spray fenders, is spray and splash suppressed, as measured by the Video-Based spray testing procedure?

3. Is there a difference in splash and spray suppression between the 1997 and 1985 tractors, as measured by the Video-Based spray testing procedure?

4. How similar are the results of the laser and video-based methodologies?

Experimental Setup

Test Pad Setup and Apparatus

The test pad setup used for the video-based method was identical to the test pad setup used for the laser method with the exception of several pieces of equipment. Each side of the test pad was flanked by a Pulnix TM-6CN CCD camera fitted with an Olympus 2.76 - 5.91 inch lens (70 - 150 mm), a 2x teleconverter, and a neutral density filter. The video was digitized with Video Maker video capture boards at 192 x 144 pixel resolution. Each camera filmed a target board which was painted with 16 horizontal and 12 vertical black and white squares measuring 7.68 x 7.68 inches (195 x 195 mm) each. Around the perimeter of each board existed a black 1.57 inch (40 mm) border. The target boards were 31.5 inches (800 mm) above the surface of the test track. Video-based data collection was initiated when an infrared switch, placed up range to the black and white cameras, was triggered by the approaching truck. See Figure 14 for a schematic of the layout of the video-based data collection method. Splash and spray data were collected at 12.5 frames per second, a total of 100 frames (note: only video frames corresponding to the time interval of recording for the laser method were used in processing data for comparison of the two methods).

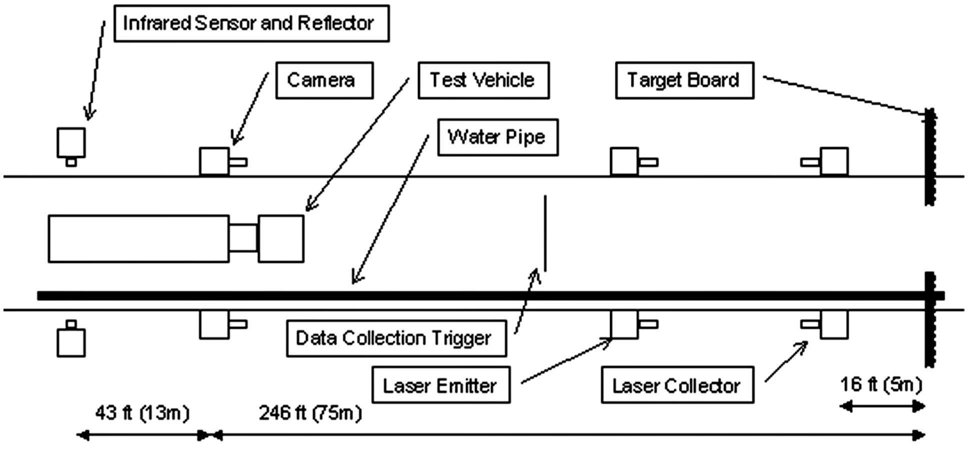

Figure 14. *A schematic of the layout of the video-based data collection method.*

Calculation of APC

Arrival at an average percent contrast, APC, for the video-based method consisted of a series of steps. Step 1 was to convert each recoded video to a series of 256-level (8-bit) grayscale bitmapped images. Step 2 consisted of the generation of the 'control' image, which is determined from the first frame of video recorded for each run, before there is any spray present. For the control image, the outer boundaries of each of the grid squares within the video image were located and an average gray value (AGV) of each grid square was calculated. The AGV was the brightness of the grid square on a scale of 0 to 255, with 0 being black and 255 white. Step 3 was to calculate the contrast of each grid square, with the exception of the outer ring of squares. Contrast was equal to the average difference in AGV, or brightness, of the squares to the top, left, right, and bottom of each square. For example, if the squares were numbered 1 to 16 across and 1 to 12 down, the top left square would be 1,1 and the bottom right 16,12 so, with I = :

$$\mathrm{Contrast}_{i,j} = \frac{(\mathrm{AGV}_{i,j-1} - \mathrm{AGV}_{i,j}) + (\mathrm{AGV}_{i-1,j} - \mathrm{AGV}_{i,j}) + (\mathrm{AGV}_{i+1,j} - \mathrm{AGV}_{i,j}) + (\mathrm{AGV}_{i,j+1} - \mathrm{AGV}_{i,j})}{4}$$

Where i = 2 to 15, j = 2 to 11

Step 4 consisted of calculating the AGV for all grid squares for the video images of interest, i.e. the images where spray is present. As part of this Step, the outline of the target boards is tracked within each image to reduce the effects of camera shake as the truck passes the camera stands. Step 5 consisted of calculating the percent contrast of each test image relative to the control image, where percent contrast is defined as:

$$\%\ \mathrm{Contrast}_{i,j} = \frac{\mathrm{AGV}_{i,j\ \text{test image}}}{\mathrm{AGV}_{i,j\ \text{control image}}} \times 100; \text{ where } i=2 \text{ to } 15,\ j = 2 \text{ to } 11$$

The average values of all processed images were then calculated. For each grid square, the average of the percent contrast values of all images were calculated, giving an APC value for each grid square. By averaging the contrast of all grid squares for all images, an overall APC was obtained. Further explanation and examples of the processing of the video images are presented in Mousley, Watkins, & Seyer (1997).

Statistical Analysis

The procedures for experiment two were identical to experiment one. Pilot test runs were analyzed using a univariate analysis of variance with spray treatment (6) as the independent variable and Figure of Merit as the dependent variable. The basic question is which device, if any, reduces the production of splash and spray to the greatest degree.

For full protocol testing the data were evaluated using analysis of variance (ANOVA) procedures. Three-way fixed effects models (two levels of speed, four levels of wind, and four levels of vehicle configuration) were fitted to the data. Checks were run to see if any first-order interactions of the three main effects added significantly to the predictive power of simple main-effects models. Three basic questions were asked in the experiment:

1. When the 1997 tractor-trailer is fitted with spray fenders, is spray and splash suppressed, i.e., are vehicle configurations one and two different?

2. When the 1985 tractor-trailer is fitted with spray fenders, is spray and splash suppressed, i.e., are vehicle configurations three and four different?

3. Is there a difference is splash and spray suppression between the 1997 and 1985 tractor-trailers, i.e., are vehicle configurations one and two different from vehicle configurations three and four?

RESULTS

LASER-BASED PROTOCOL

Pilot Test Analysis

Results of the pilot test indicated no significant differences among the pilot configurations, i.e. among the five spray pilot configurations and the 1985 tractor-trailer baseline pilot configuration, F(5, 42) = 1.85, $p > .05$. Although there were no significant differences between the six configurations Pilot Configuration Three produced the least amount of spray. Since Pilot Configuration Three produced the least amount of spray, it was tested further. Average Figures of Merit and 95% confidence intervals for the laser method for each of the pilot configurations and the no treatment baseline pilot configuration are presented in Table 2.

Pilot Test Spray Treatments	Mean Figures of Merit	95% Confidence Intervals
Pilot Baseline Configuration (OEM flaps)	35.8	±19.27
Pilot Configuration One (OEM flaps and spray fenders)	29.9	±7.36
Pilot Configuration Two (OEM flaps and spray fenders with brush)	38.9	±7.45
Pilot Configuration Three (OEM flaps and spray fenders)	42.3	±9.81
Pilot Configuration Four (spray brush)	35.4	±5.27
Pilot Configuration Five (artificial grass)	23.7	±13.94

Table 2. *Laser method mean Figures of Merit and 95% confidence intervals for each configuration for the pilot test spray treatments. For each pilot configuration the 1985 tractor van trailer was employed.*

Full Protocol Analysis

Some 256 (8 x 2 x 4 x 4) data points (i.e., average laser readings) were available to be fitted in the ANOVA model. That is to say, eight readings were collected under each of 32 different situations (2 speeds x 4 wind conditions x 4 vehicle configurations). The model that was chosen as the best fit to the data included three main effects (Speed, Wind, Configuration) and one first order interaction (Wind by Configuration). This model fit the data rather well, accounting for 71 percent of the variance in the laser readings. F tables for the model and ANOVA are presented in Tables 3 and 4, respectively. The average (mean) laser readings for the four vehicle configurations are presented in Table 5.

Source	DF	Sum of Squares	Mean Square	F Value	p
Model	16	23139.57813	1446.22363	37.59	<.0001
Error	239	9194.20996	38.46950		
Corrected Total	255	32333.78809			

Table 3. *F table for the model for the laser based methodology.*

Source	DF	Type 1 Sum of Squares	Mean Square	F Value	p
Speed	1	4335.39941	4335.39941	112.70	<.0001
Wind	3	3969.45605	1323.15202	34.39	<.0001
Configuration	3	12543.36230	4181.12077	108.69	<.0001
Wind * Configuration	9	2291.36035	254.59559	6.62	<.0001

Table 4. *F table for the ANOVA for the laser based methodology.*

Configuration	Mean
1. 1997 Tractor, OEM Flaps and no Spray Fenders	75.38
2. 1997 Tractor, OEM Flaps and Spray Fenders	75.05
3. 1985 Tractor, OEM Flaps and no Spray Fenders	59.71
4. 1985 Tractor, OEM Flaps and Spray Fenders	63.15

Table 5. *The average laser based methodology Figures of Merit for the four vehicle configurations.*

Before answering the three research questions originally posed, it should be recognized that there is a significant interaction term in the model (Wind by Configuration). In light of this interaction, consider the first question that was asked: Are vehicle configurations one and two different? Looking at the means for vehicle configurations one and two, it would appear that there is little if any difference between these two conditions (75.38 vs. 75.05). But, it is possible that vehicle configuration one could have been significantly larger than vehicle configuration two under two wind conditions, and significantly smaller under the other remaining two wind conditions. If that were the case, then to say that there is no difference between vehicle configurations one and two would be misleading. Accordingly, the difference between vehicle configurations one and two was tested for each of the four wind conditions. In similar fashion, the difference between vehicle configurations three and four was tested under each of the four wind conditions and the difference between vehicle conditions one plus two and vehicle conditions three plus four was tested under each of the four wind conditions. The results are presented in Table 6. In the significance tests performed, the critical values for t (df=239) were 2.893 for $\alpha = 0.05$ and 3.384 for $\alpha = 0.01$. These critical values are Bonferroni corrections that take into account the fact that 12 tests are being carried out on the same dataset.

For the two 1997 tractor-trailer combinations, the addition of a spray fender did not appear to have much effect, as measured by the SAE laser procedure. Only in the right cross wind condition (at 3-10 mph) (4.83-16.09 kph) is a significant difference for tractors equipped with spray fenders, and that difference is in an unusual direction, i.e., spray fenders were associated with a significant increase in splash and spray. Similarly, spray fenders did not have much effect on splash and spray suppression for the 1985 tractor-trailer combinations. Only in the left crosswind condition (at 3-10 mph) (4.83-16.09 kph) is a significant reduction in splash and spray observed. Finally, splash and spray suppression (again, as measured by the SAE laser procedure) is significantly better in the 1997 tractor-trailer combinations than in the 1985 tractor-trailer combinations. This statement is true for all four wind conditions.

Vehicle Configuration	Wind Condition	Difference in Means	t	Significance
One – Two	0-3 mph	- 0.563	- 0.257	NS
	3-10 mph Tail	- 3.172	- 1.447	NS
	3-10 mph Left	- 5.766	- 2.629	NS
	3-10 mph Right	10.781	4.916	< 0.01
Three – Four	0-3 mph	- 4.250	- 1.938	NS
	3-10 mph Tail	2.203	1.005	NS
	3-10 mph Left	- 6.953	- 3.171	<0.05
	3-10 mph Right	- 4.750	- 2.166	NS
(One + Two) - (Three + Four)	0-3 mph	17.016	10.947	< 0.01
	3-10 mph Tail	16.625	10.721	< 0.01
	3-10 mph Left	9.469	6.107	< 0.01
	3-10 mph Right	12.032	7.759	< 0.01

Table 6. *Results of the significance tests performed examining for each of the four wind conditions the difference between vehicle configurations one and two, the difference between vehicle configurations three and four, and the difference between vehicle conditions one plus two and vehicle conditions three plus four.*

VIDEO-BASED PROTOCOL

Pilot Test Analysis

Results of the pilot test indicated no significant differences among the pilot configurations including the Pilot Baseline Configuration, F(5, 32) = 1.14, p > .05. Although there were no significant differences between the six configurations Pilot Configurations Two and Three produced the least amount of spray. These results are consistent with the results of the laser method pilot test that indicated Pilot Configurations Two and Three performed similarly. Average Percent Contrasts and 95% confidence intervals for the video based method for each pilot configuration are presented in Table 7.

Pilot Test Spray Treatments	Average Percent Contrasts	95% Confidence Intervals
Pilot Baseline Configuration	43.1	±8.1
Pilot Configuration One	45.5	±9.9
Pilot Configuration Two	47.9	±5.4
Pilot Configuration Three	47.9	±34.6
Pilot Configuration Four	46.4	±13.9
Pilot Configuration Five	34.9	±4.2

Table 7. *Video based method average Figures of Merit and 95% confidence intervals 95% confidence intervals for each configuration for the pilot test spray treatments.*

Full Protocol Analysis

The ANOVA model that best fit the Australian video-based data was of the same form as the model developed in experiment one. It included three main effects and one first-order interaction (Wind by Configuration) and explained 69 percent of the variance in the measurements. It should be noted that data were available for only 229 of the 256 runs in this experiment. The degrees of freedom in the error term were reduced to 212. F tables for the model and ANOVA are presented in Tables 8 and 9, respectively. The average (mean) laser readings for the four vehicle configurations are presented in Table 10.

Source	DF	Sum of Squares	Mean Square	F Value	P
Model	16	16641.60440	1040.10027	29.94	<.0001
Error	212	7364.06582	34.73616		
Corrected Total	228	24005.67022			

Table 8. *F table for the model for the video based methodology.*

Source	DF	Type 1 Sum of Squares	Mean Square	F Value	p
Speed	1	4001.912765	4001.912765	115.2	<.0001
Wind	3	2511.990753	837.330251	24.11	<.0001
Configuration	3	8226.470705	2742.156902	78.94	<.0001
Wind * Configuration	9	1901.230175	211.247797	6.08	<.0001

Table 9. *F table for the ANOVA for the video based methodology.*

Configuration	Mean
1. 1997 Tractor, OEM Flaps and no Spray Fenders	80.54
2. 1997 Tractor, OEM Flaps and Spray Fenders	81.41
3. 1985 Tractor, OEM Flaps and no Spray Fenders	67.25
4. 1985 Tractor, OEM Flaps and Spray Fenders	73.24

Table 10. *The average photo readings for the four vehicle configurations.*

The three questions of interest are again considered for each of four Wind by Configuration situations. The critical t's (with 212 df) for this assessment were 2.897 for $\alpha = 0.05$ and 3.390 for $\alpha = 0.01$. Answers to these questions are shown in the table 11.

Vehicle Configuration	Wind Condition	Difference in Means	T	Significance
1 - 2	0-3 mph	-2.442	-1.153	NS
	3-10 mph Tail	-3.660	-1.639	NS
	3-10 mph Left	-8.088	-3.881	<0.01
	3-10 mph Right	10.734	5.068	<0.01
3 - 4	0-3 mph	-6.476	-3.057	<0.05
	3-10 mph Tail	-1.334	-0.570	NS
	3-10 mph Left	-11.230	-4.352	<0.01
	3-10 mph Right	-4.933	-2.161	NS
(1+2) - (3+4)	0-3 mph	12.339	8.238	<0.01
	3-10 mph Tail	9.317	5.761	<0.01
	3-10 mph Left	9.836	5.932	<0.01
	3-10 mph Right	11.429	7.341	<0.01

Table 11. *Results of the significance tests performed examining for each of the four wind conditions the difference between vehicle configurations one and two, the difference between vehicle configurations three and four, and the difference between vehicle conditions one plus two and vehicle conditions three plus four.*

For the two 1997 tractor-trailer configurations (configurations one and two) the addition of spray fenders had no demonstrable effect in the no-wind (i.e., 0-3 mph) (0 - 4.83 kph) and light (3-10 mph) (4.83 - 16.09 kph) tail wind conditions. In the left and right cross wind conditions (at 3-10 mph) (4.83 - 16.09 kph), the addition of fenders is associated with significant decreases and increases in splash and spray, respectively (as measured by the Australian photo-based procedure). For the 1985 tractor-trailer configurations (configurations three and four), spray fenders provided no demonstrable benefit in the light tail wind condition and right cross wind condition, but were of significant benefit in the no-wind condition and left crosswind condition. In all wind conditions, the two 1997 tractor-trailer configurations (configurations three and four) produced significantly less splash and spray than the two 1985 tractor-trailer configurations (configurations one and two).

COMPARISON OF LASER AND VIDEO-BASED METHODOLOGIES

In addition to the three intra-experiment questions, this study also sought to determine if the two procedures being evaluated, the SAE laser-based methodology and the Australian video based procedure, yielded comparable results. Specifically, how well do test results obtained from the two procedures correlate?

In Table 12 the direct comparison of experiments one and two are presented. For the most part, the two procedures yield very similar results. For the 1997 tractor-trailer configurations without (configurations one) and with (configuration two) spray fenders, all findings are in the same direction. The one difference: the Australian procedure shows a significant difference in the left cross wind situation, the SAE procedure does not.

Vehicle Configuration	Wind Condition	SAE Laser Procedure		Australian Photo Procedure	
		Difference in Means	Significance	Difference in Means	Significance
One – Two	0-3 mph	- 0.563	NS	-2.442	NS
	3-10 mph Tail	- 3.172	NS	-3.660	NS
	3-10 mph Left	- 5.766	NS	-8.088	<0.01
	3-10 mph Right	10.781	<0.01	10.734	<0.01
Three – Four	0-3 mph	- 4.250	NS	-6.476	<0.05
	3-10 mph Tail	2.203	NS	-1.334	NS
	3-10 mph Left	- 6.953	<0.05	-11.230	<0.01
	3-10 mph Right	- 4.750	NS	-4.933	NS
(One+Two) - (Three+Four)	0-3 mph	17.016	<0.01	12.339	<0.01
	3-10 mph Tail	16.625	<0.01	9.317	<0.01
	3-10 mph Left	9.469	<0.01	9.836	<0.01
	3-10 mph Right	12.032	<0.01	11.429	<0.01

Table 12. *Results of the direct comparison of the laser and video based methodologies. As can be see the two procedures yield very similar results.*

For the 1985 tractor-trailer configurations without and with spray fenders (configurations three and four), no significant differences are seen in the tail wind and left crosswind conditions (although in the tail wind condition, the observed difference is negative in the SAE procedure and positive in the Australian procedure). In the right cross wind condition, spray fenders are seen to be a significant improvement in both the SAE procedure (at $\alpha = 0.05$) and the Australian procedure (at $\alpha = 0.01$). In the no-wind condition, no benefit is seen for fenders in the SAE procedure; using the Australian procedure, a benefit is observed (at $\alpha = 0.05$).

When the 1997 tractor-trailer configurations are compared to the 1985 tractor-trailer configurations, both the SAE procedure and the Australian procedure show significant reductions in splash and spray in all four wind conditions (at $\alpha = 0.01$).

Finally, in Figure 15, the Australian video based data are regressed on the SAE laser-based data. There were 229 runs for which both photo data and laser data were available. The correlation between the two measures is quite good (+ 0.753).

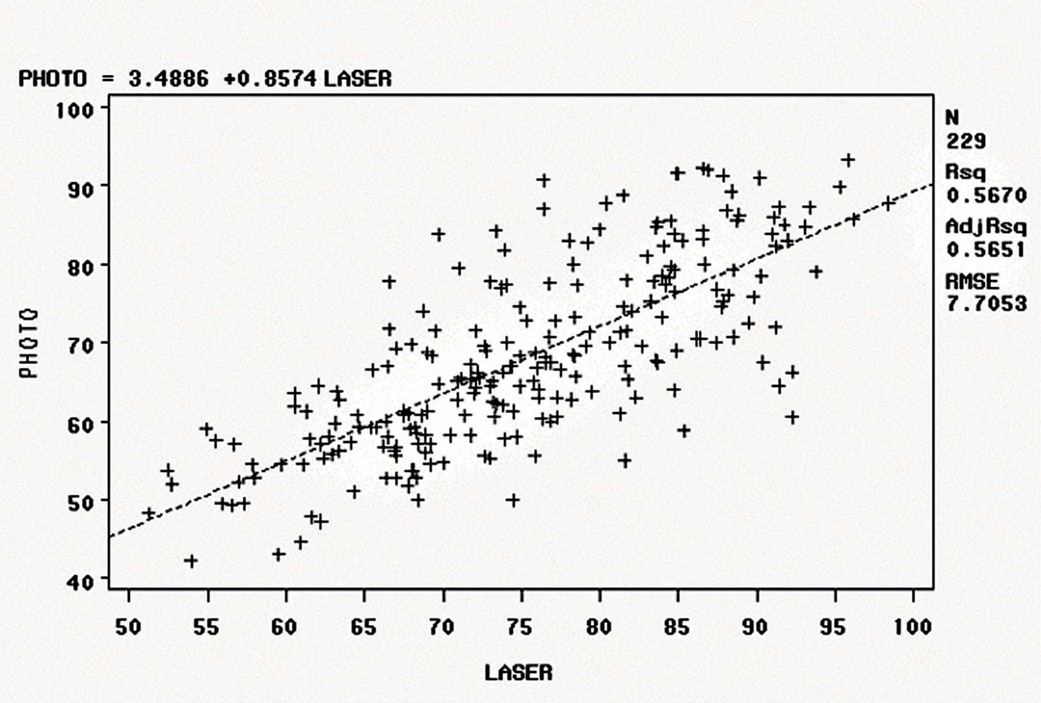

Figure 15. *Depiction of the Australian video based data regressed on the SAE laser-based data. The correlation between the two measures was + 0.753.*

DISCUSSION

Note, throughout this Discussion the FOM term refers solely to the FOM obtained during a single trial (average of either two or four laser measures) while mean Figures of Merit refers to the average of all Figures of Merit for the referenced conditions or configurations.

SPRAY REDUCTION DEVICES AND VEHICLE AERODYNAMICS

It should be recognized that the present investigation utilized a single 1997 Freightliner tractor, a single 1985 Freightliner tractor, and a single 1984 Trailmobile Incorporated van trailer. In light of the use of only two tractors and a single trailer, a veridical generalization between the experimental configurations and any real world configurations is limited at best. To allow for greater generalization many different tractor-trailer configurations would have to be tested under identical circumstances. Due to time and financial limitations, this was not prudent. However, in light of the marked differences between the 1997 and 1985 tractor-trailer configurations it is reasonable to assume some level of generalization between the experimental setup/results and the real world. The following discussion addresses differences between and provides discourse relating to only those tractor-trailer combinations tested as part of this study. Any generalizations beyond these results are to be made by the reader and should be done so with caution.

Comparison of Multiple Spray Reduction Devices

A central question of the present investigation is whether the addition of spray devices to two different large trucks with trailers can reduce spray. Large trucks that produce less spray will increase the levels of safety for all drivers by allowing greater visibility in potentially hazardous wet weather conditions. To address this question, the spray produced by five different spray device configurations outfitted to a 1985 large truck were compared against a baseline condition using the SAE J2245 laser methodology. The spray device configurations included a commercially available fender system, a commercially available fender and brush system, a commercially unavailable fender system, a brush system, and a system of flaps on which existed a material similar to artificial grass. Statistically, no device tested produced significantly more or significantly less spray than the baseline configuration. When the mean Figures of Merit for each configuration are examined, the most effective device was a fender system. However, it reduced spray by only 7.5% relative to the baseline configuration. The results of the video-based methodology are consistent with the laser methodology results; no significant differences were found between the amount of spray produced with the spray-reducing devices fitted and the baseline configuration. From the initial results obtained in this investigation, the response to the central question is that the addition of spray-reduction devices to a 1985 tractor-trailer configuration does not significantly reduce the production of spray.

Spray Device Efficacy

The conclusion that spray reduction devices do not reduce spray from a tractor-trailer configuration during wet weather conditions should be accepted with caution, as there are several unaddressed critical issues. These include the efficacy of devices to produce less spray on a tractor-trailer configuration in wet weather under a variety of wind conditions and vehicle speeds, the efficacy and influence of a tractor-trailer aerodynamics on the production of spray in a variety of wind conditions and vehicle speeds, and whether or not it is the addition of spray devices or improved tractor-trailer aerodynamics that could produce the most significant decrements in spray production. To address these issues four tractor-trailer configurations (spray devices present and not present on a 1985 tractor-trailer configuration and spray devices present and not present on a 1997 tractor-trailer configuration) were tested fully at vehicle speeds of 55 and 65 mph (88.5 and 104.59 kph) with two of the four configurations being considered baseline due to the absence of any spray devices beyond OEM spray reduction flaps. Four separate wind conditions were employed: slowwinds, moderate tailwinds, and moderate right and left crosswinds. Note, right and left crosswinds are more productive of spray on the downwind side of the vehicle. Tailwinds of moderate velocity (up to 10 mph) (16.09 kph) spread the spray produced on either side of the vehicle, more so than do slowwinds.

The results of the present investigation indicated that the addition of a spray reduction device to a 1997 tractor-trailer configuration resulted in a mean Figures of Merit decrease in spray production of only .33%. Mean Figures of Merit for the 1997 tractor-trailer configurations without and with a spray reduction device were 75.38 and 75.05% respectively. The lack of a marked reduction of spray was also evident with the 1985 tractor-trailer configuration without and with spray reduction devices. Specifically, the mean Figures of Merit for the 1985 tractor-trailer configurations without and with a spray reduction device were 59.71 and 63.75% respectively. In fact, the only significant reduction in spray was exhibited in the left crosswind condition. These results provide support for the contention that the addition of a spray reduction device to either a 1997 Freightliner tractor-trailer configuration or a 1985 Freightliner tractor-trailer configuration will not result in a significant reduction in the production of spray in wet weather.

VEHICLE AERODYNAMICS

An important issue is whether improving the aerodynamics of a large truck can facilitate a reduction in spray. To address this issue it is necessary to compare the 1997 tractor-trailer configurations with improved aerodynamics with the 1985 tractor-trailer configurations with poorer aerodynamics. Results indicated the two 1997 tractor-trailer configurations with improved aerodynamics produced significantly less spray than the two 1985 tractor-trailer configurations with poorer aerodynamics. The combined mean Figures of Merit across all four wind conditions for both the 1997 and both the 1985 tractor-trailer configurations was 75.22 and 61.43%, respectively. This represents a

13.8% average reduction in spray due to improved tractor aerodynamics alone. These dramatic differences in the amount of spray produced remain even when the mean Figures of Merit of the 1997 and 1985 tractor-trailer no spray device configurations are compared (75.38 and 59.71% respectively with a 15.7% reduction in spray) and when the 1997 and 1985 tractor-trailer spray device configurations are compared (75.05 and 63.15 respectively with an 11.9% reduction in spray). These results provide initial support for the contention that improved aerodynamics can significantly reduce the amount of spray produced by large trucks.

It is clear from the data presented above that an improvement in the aerodynamics of a tractor-trailer configuration can reduce the amount of spray generated by a 1997 tractor-trailer configuration as compared to a 1985 tractor-trailer configuration, and this improvement remains independent of the addition of a spray device. These results also indicate that tractor-trailer aerodynamics, versus the application of aftermarket devices purported to reduce spray, produce more significant decrements in spray production.

DISADVANTAGES OF SPRAY DEVICES

There are several disadvantages to the use of aftermarket spray devices that became evident during the course of this research project or were relayed to the research team via truck and truck equipment manufacturers. Anecdotal evidence from the research team indicated they had great difficulty attaching some of the spray devices. In one case, an entire suite of fenders could not be fitted to a tractor-trailer configuration because it would have required excising a significant portion of the engine compartment cowling to attach the steering axle spray reduction devices. In several cases the time required to 'suite' an entire tractor-trailer combination exceeded two full work days for two to three installers. This translates into significant labor costs. Lastly, there is some reluctance by truck fleets to use some spray devices due to the multiple problems experienced when the tractor or trailer experiences a flat tire. In particular, spray devices can be destroyed when a tire 'blows.' A second problem faced from the flat tire scenario is the time required to remove and replace the destroyed spray device.

Laser and Video Based Testing Methodologies

Employing both testing methodologies in parallel consisted of having each methodology collect spray data simultaneously for each test run. Figures of Merit and Average Percent Contrasts were calculated accordingly for each methodology. A benefit of employing the SAE J2245 laser and the video-based methodologies is that each could be used to support and backup the results of the other.

The strong correlation (r = 0.753) between the laser and video-based methodologies provide support for the contention that the amount of spray measured by the SAE J2245 laser and the video-based methodologies were very similar. This finding is in alignment with previous research that showed a .85 correlation between the laser methodology and the digitization methodology (Koppa, Pezoldt, Zimmer, Deliman, & Flowers; 1990).

FUTURE RESEARCH

A necessary component of research is the assessment of what issues remain unaddressed. An issue not addressed in the present investigation is how much spray is produced at differing distances from the tractor-trailer given good vehicle aerodynamics and how this ‘cloud’ of spray changes in shape and density over time. Certainly, the current research suggests there are unacceptable amounts of spray produced within several feet of a large truck regardless of the addition of a variety of spray devices. However, knowledge of the formation and shape of the spray cloud over time would allow spray device and large truck manufacturers to better design devices.

A second issue that requires further investigation is how the research methodology employed in examining spray from large trucks can be altered to allow for faster and more efficient testing while retaining high levels of reliability. Faster and more efficient methodologies would reduce the cost of testing and encourage a more iterative testing and design approach to spray device development. For example, a significant challenge faced in the present investigation was testing particular wind directions and wind speeds. Many times the researchers on the current project were forced to postpone testing in order to get specific wind directions and wind speeds.

LIMITATIONS

Throughout the course of this project several limitations were identified that should be delineated and addressed in future research. The most salient limitation was the inability to attach the entire suit of fenders for Pilot Configuration Three (and later used for Full Protocol testing Configurations Two and Three) to the tractor-trailer configuration. Specifically, mounting the fenders to the steering axle of the less aerodynamic tractor and to the steering and tandom axle of the more aerodynamic tractor was not practical due to the need to significantly modify each of the tractor’s support structure for the OEM quarter panels and to modify the OEM quarter panels and nose sections. As a result the fender suit was not complete and this may have reduced the overall effectiveness of the system to reduce splash and spray.

A tertiary limitation was the inability to contact the manufacturers of all potentially available splash and spray reduction devices due to limited or incorrect contact information or the manufacturers decision not to provide devices for testing. As a result of manufacturers inability to be contacted or to return inquiries it is impossible for this report to determine with 100% certainty that all devices fail to significantly reduce splash and spray.

A second tertiary limitation was the ability to collect data in a timely manner.

This limitation was a result of variations in wind speed and direction between experimental runs, days, and months. For example, once all data was collected for a particular wind direction the research staff would have to wait days and sometimes weeks before a new wind direction was presented and data could again be collected. While this did not affect the accuracy and reliability of data collection it certainly did impact the proposed timeframe of the project.

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Appendix A - *Search Terms*

splash
spray
splash and spray
truck and spray
truck and splash
vehicle splash
vehicle spray
suppressant
splash suppressant
spray suppressant
truck and suppressant
vehicle and suppressant
splash suppress
spray suppress
splash suppress
spray suppress

Appendix B - *Search Results*

Manufacturers

G-P Manufacturing Incorporated
Freightliner Corporation
Lancastor Colony Corporation
Truck Safety of America
Monsanto Corporation
Peterbilt
Volvo
Mercedes
Mack Truck
Jeco Plastic Manufacturing
PACCAR
Solutia/Symplastics
Schlegel
DynaPlas
Bridgestone Corporation
Fleet Engineers Incorporated
Bess Tech Associates
Air Fenders

Individuals

Parlok Ab Oy - Finland
Claude Chassing - France
Michael George Marsh - Great Britain
Jurge Heinz-Henning

Appendix C - *Laser Method Pilot Test Data*

CONFIGURATION	RUN	SCORE
Pilot Baseline	1	35.5
	2	22
	3	16.5
	4	89
	5	20
	6	41.5
	7	30
	8	32
One	1	20.5
	2	22
	3	36
	4	20
	5	34
	6	45
	7	33
	8	28.5
Two	1	25.5
	2	34
	3	36.5
	4	48.5
	5	36.5
	6	32.5
	7	50.5
	8	47.5
Three	1	40.5
	2	94
	3	68
	4	50.5
	5	94.5
	6	90.5
	7	91
	8	80
Four	1	58.5
	2	34
	3	33
	4	22.5
	5	24.5
	6	28
	7	39.5
	8	43.5
Five	1	19
	2	24.5
	3	37
	4	19.5
	5	24.5
	6	16
	7	24.5
	8	24.5

Appendix D - *Laser Method 55 and 65 MPH Data*

			RUN							
SPEED	WIND	CONF	1	2	3	4	5	6	7	8
55	0-3 MPH	1	74.50	85.75	78.50	91.50	91.00	85.50	79.00	85.50
		2	86.25	83.00	83.75	89.25	82.25	93.25	78.50	76.75
		3	61.75	53.75	66.50	65.00	50.00	55.75	50.00	64.75
		4	70.50	70.00	68.50	72.75	68.00	70.50	71.50	65.00
	3-10 MPH TAIL	1	91.25	84.25	83.75	88.75	72.50	82.25	84.75	85.50
		2	86.00	89.75	87.25	86.00	90.75	91.50	87.75	92.25
		3	64.00	75.50	64.25	74.50	77.00	70.75	72.00	69.50
		4	68.75	65.75	68.75	57.75	67.00	74.50	63.00	70.00
	3-10 MPH LFT CROSS	1	60.75	71.75	77.25	80.00	69.00	80.00	69.50	67.00
		2	71.25	79.75	66.25	76.00	67.50	63.00	92.00	87.25
		3	60.00	77.50	66.50	60.75	69.00	54.50	52.75	59.25
		4	75.50	73.25	72.75	69.50	72.75	70.50	71.00	71.00
	3-10 MPH RGT CROSS	1	85.00	79.25	78.00	86.75	82.75	79.25	81.00	77.75
		2	65.25	65.50	77.25	67.00	61.25	56.75	73.25	59.25
		3	62.00	60.00	57.75	60.50	58.25	52.75	63.50	60.75
		4	66.50	73.00	64.50	67.50	70.00	60.00	51.00	58.25
65	0-3 MPH	1	66.75	63.00	74.00	87.75	82.25	74.00	59.25	69.50
		2	77.75	67.00	68.25	64.50	71.50	84.75	72.75	77.25
		3	54.50	57.25	69.25	63.75	67.00	43.00	55.50	68.25
		4	55.50	56.25	55.50	56.00	59.00	59.75	54.75	60.50
	3-10 MPH TAIL	1	64.50	75.75	83.75	64.75	77.75	74.75	84.25	83.25
		2	74.50	75.25	85.25	84.50	78.25	64.00	76.50	83.00
		3	67.50	58.25	64.50	60.50	67.25	57.00	52.75	63.50
		4	63.75	59.25	65.25	57.00	60.25	61.00	62.75	58.75
	3-10 MPH LFT CROSS	1	69.75	71.25	67.00	62.75	65.50	71.50	68.25	60.75
		2	70.75	87.00	66.25	81.75	67.50	79.50	75.25	73.25
		3	59.00	57.00	62.75	56.25	51.75	57.50	53.75	52.75
		4	62.50	55.25	61.25	56.75	65.00	68.75	58.00	58.50
	3-10 MPH RGT CROSS	1	70.00	61.00	67.75	83.00	66.25	60.50	63.00	61.25
		2	70.00	62.25	57.00	54.50	55.00	56.50	61.25	68.00
		3	47.25	48.25	49.50	49.25	52.00	49.50	52.25	42.25
		4	55.25	44.50	53.75	58.00	47.75	59.25	54.50	58.00

Appendix E - *Video Based Method Pilot Data*

CONFIGURATION	RUN	SCORE
Pilot Baseline	1	49.2
	2	52.7
	3	25.5
	4	.
	5	40.7
	6	46.6
	7	45.4
	8	41.7
One	1	49.8
	2	31.9
	3	58.6
	4	31.7
	5	47.0
	6	43.1
	7	56.2
	8	.
Two	1	.
	2	.
	3	42.8
	4	48.9
	5	49.5
	6	50.2
	7	.
	8	.
Three	1	.
	2	.
	3	50.2
	4	77.2
	5	.
	6	.
	7	27.1
	8	36.9
Four	1	66.1
	2	64.4
	3	39.6
	4	38.6
	5	30.9
	6	26.2
	7	38.5
	8	66.6
Five	1	36.9
	2	29.9
	3	37.1
	4	28.9
	5	44.4
	6	32.0
	7	36.8
	8	33.2

Appendix F - *Video Based Method 55 and 65 MPH Data*

			RUN							
SPEED	WIND	CONF	1	2	3	4	5	6	7	8
55	0-3 MPH	1	87.80	96.20	84.00	85.00	90.20	88.80	93.80	84.50
		2	88.90	92.00	91.00	88.40	91.20	95.90	90.30	87.50
		3	60.50	68.10	77.50	73.20	74.50	62.90	68.40	69.70
		4	86.20	87.40	78.30	75.30	.	86.40	72.10	75.80
	3-10 MPH TAIL	1	87.90	86.60	84.70	81.50	89.50	.	93.10	88.70
		2	.	95.30	93.40	91.10	76.40	84.90	98.40	86.60
		3	84.70	.	72.10	74.90	73.70	76.80	91.20	82.70
		4	.	78.50	75.90	73.90	.	.	.	.
	3-10 MPH LFT CROSS	1	71.40	66.60	84.20	78.30	84.90	86.70	72.60	66.50
		2	81.30	84.50	92.30	88.20	90.40	82.30	86.90	91.40
		3	66.40	76.80	65.50	64.50	72.70	61.10	66.40	.
		4	.	.	.	.	.	.	.	.
	3-10 MPH RGT CROSS	1	91.80	84.70	81.70	88.10	79.20	88.50	83.00	83.40
		2	71.80	71.10	74.00	74.30	74.50	66.20	78.40	65.40
		3	73.80	76.90	61.50	.	70.50	68.30	72.00	68.60
		4	.	.	74.90	83.70	.	.	64.30	68.90
65	0-3 MPH	1	76.00	76.10	82.10	80.40	84.10	68.70	68.20	79.10
		2	66.60	.	78.40	91.40	81.70	83.60	77.20	78.60
		3	59.70	64.10	67.00	79.50	74.40	59.50	67.00	69.30
		4	75.90	66.90	72.60	68.90	67.90	63.10	70.00	73.30
	3-10 MPH TAIL	1	73.00	89.80	69.70	.	73.00	.	73.40	86.60
		2	81.50	87.90	83.70	80.00	84.40	76.10	84.80	85.30
		3	76.90	71.80	62.00	77.30	71.80	69.20	67.00	60.50
		4	63.20	64.60	81.80	68.40	76.30	67.80	78.20	85.40
	3-10 MPH LFT CROSS	1	68.00	79.30	81.60	70.90	72.30	69.50	74.90	67.50
		2	88.50	76.40	73.80	73.90	76.50	71.00	83.20	84.00
		3	54.90	56.70	63.40	63.40	67.80	55.50	52.40	58.00
		4	73.20	73.00	69.00	67.00	70.90	69.00	74.70	68.30
	3-10 MPH RGT CROSS	1	80.60	81.30	83.60	78.00	72.20	92.30	77.30	67.50
		2	74.10	73.40	62.20	69.20	81.60	.	61.30	76.50
		3	62.20	51.20	55.90	56.50	52.70	57.30	57.00	53.90
		4	62.40	60.90	68.00	62.70	61.60	65.70	57.80	66.50

Appendix G - *Repeated Measures Analysis Explanation*

Repeated Measures Analyses

Repeated-measures analyses are generally of two types. In the first type, the same subject is tested once under several (or potentially all) of the various experimental conditions or situations in the experiment. In this design the subjects are, in effect, their own control (referred to here as Scenario 1). In the second type of repeated-measures analysis, each subject within a given experimental situation is tested several times. This type of repeated-measures design is really a MANOVA design with each repeated test serving as a different dependent variable (referred to here as Scenario 2).

Hypothetical Repeated Measures Experiment (Scenario 1)

If the tractor trailer is considered to be the "subject" in our experiment, and if 32 tractor trailers had been available to study splash and spray effects, we might have run the following experiment. 16 tractor-trailers from model year 1985 and 16 from model year 1997. Half of the 32 tractor-trailers would have been equipped with OEM flaps and spray fenders and half would not have been equipped with OEM flaps and spray fenders. Each of the 32 tractor trailers would then have been run under eight different experimental situations as shown below for a total of 256 runs (32 tractor trailers by 1 run per experimental situation by 8 experimental situations). The following configurations highlight this design.

TRUCK	YEAR	SPLASH DEVICE	SPEEDS	WIND COND.	RUNS
1	1985	No Fenders	55 and 65 MPH	All Four Wind Cond.	8
2	1985	Fenders	55 and 65 MPH	All Four Wind Cond.	8
3	1985	No Fenders	55 and 65 MPH	All Four Wind Cond.	8
.					
.					
.					
16	1985	Fenders	55 and 65 MPH	All Four Wind Cond.	8
17	1997	No Fender	55 and 65 MPH	All Four Wind Cond.	8
18	1997	Fenders	55 and 65 MPH	All Four Wind Cond.	8
19	1997	No Fenders	55 and 65 MPH	All Four Wind Cond.	8
.					
.					
.					
32	1997	Fenders	55 and 65 MPH	All Four Wind Cond.	8

By the tenets of this design, each tractor-trailer is run in eight different experimental situations, and thus each tractor-trailer serves as its own control-at least across those eight experimental situations to which it was assigned.

Hypothetical Repeated Measures Experiment (Scenario 2)

In Scenario Two 32 tractor-trailers are also employed with 16 of them being model year 1985 and 16 of them being model year 1997. Half of the 32 tractor-trailers would have been equipped with OEM flaps and spray fenders and half would not have been equipped with OEM flaps and spray fenders. One tractor-trailer would be assigned to each of 32 experimental situations, but each tractor-trailer would make 8 runs under its assigned experimental situation. In sum, 256 runs would again be recorded (32 tractor-trailers in 32 different experimental situations with eight runs per situation). The following configurations highlight this design.

TRACTOR	YEAR	SPEED	SPLASH DEVICE	WIND CONDITION	RUNS
1	1985	55	No Fenders	No wind	8
2	1985	55	Fenders	No Wind	8
3	1985	55	No Fenders	Tailwind	8
4	1985	55	Fenders	Tailwind	8
5	1985	55	No Fenders	Left Cross	8
6	1985	55	Fenders	No Left Cross	8
7	1985	55	No Fenders	Right Cross	8
8	1985	55	Fenders	Right Cross	8
9	1997	55	No Fenders	No Wind	8
10	1997	55	Fenders	No Wind	8
11	1997	55	No Fenders	Tail Wind	8
12	1997	55	Fenders	Tail Wind	8
13	1997	55	No Fenders	Left Cross	8
14	1997	55	Fenders	No Left Cross	8
15	1997	55	No Fenders	Right Cross	8
16	1997	55	Fenders	Right Cross	8
17	1985	65	No Fenders	No Wind	8
18	1985	65	Fenders	No Wind	8
19	1985	65	No Fenders	Tailwind	8
20	1985	65	Fenders	Tailwind	8
21	1985	65	No Fenders	Left Cross	8
22	1985	65	Fenders	No Left Cross	8
23	1985	65	No Fenders	Right Cross	8
24	1985	65	Fenders	Right Cross	8
25	1997	65	No Fenders	No Wind	8
26	1997	65	Fenders	No Wind	8
27	1997	65	No Fenders	Tailwind	8
28	1997	65	Fenders	Tailwind	8
29	1997	65	No Fenders	Left Cross	8
30	1997	65	Fenders	No Left Cross	8
31	1997	65	No Fenders	Right Cross	8
32	1997	65	Fenders	Right Cross	8

By the tenets of this design, we entertain the notion that a subject's response to an experimental situation might vary as a function of practice, learning, fatigue, experience, etc. By allowing for eight sequential runs within an experimental situation, the existence of these sequential factors might be assessed. Ideally, the sequential runs carried out in this sort of experimentation should be standardized. For example, all runs within an experimental situation might be sequenced at 10-minute intervals.

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